Occurrence, sources, and relationships of soil microplastics with adsorbed heavy metals in the Ebinur Lake Basin, Northwest China

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Abstract: There is a lack of research on soil microplastics in arid oases considering the rapid economic development of northwestern China. Here, we studied the occurrence and sources of microplastics in soil, as well as the relationships between microplastics and adsorbed heavy metals in the Ebinur Lake Basin, a typical arid oasis in China. Results showed that (1) the average microplastic content in all soil samples was 36.15 (±3.27) mg/kg. The contents of microplastics at different sampling sites ranged from 3.89 (±1.64) to 89.25 (±2.98) mg/kg. Overall, the proportions of various microplastic shapes decreased in the following order: film (54.25%)>fiber (18.56%)>particle (15.07%)>fragment (8.66%)>foam (3.46%); (2) among all microplastic particles, white particles accounted for the largest proportion (52.93%), followed by green (24.15%), black (12.17%), transparent (7.16%), and yellow particles (3.59%). The proportions of microplastic particle size ranges across all soil samples decreased in the following order: 1000–2000 μm (40.88%)>500–1000 μm (26.75%)>2000–5000 μm (12.30%)>100–500 μm (12.92%)>0–100 μm (7.15%). FTIR (Fourier transform infrared) analyses showed that polyethylene terephthalate (PET), polypropylene (PP), polycarbonate (PC), polyethylene (PE), and polystyrene (PS) occurred in the studied soil; (3) random forest predictions showed that industrial and agricultural production activities and the discharge of domestic plastic waste were related to soil microplastic pollution, in which agricultural plastic film was the most important factor in soil pollution in the study area; and (4) seven heavy metals extracted from microplastics in the soil samples showed significant positive correlations with soil pH, EC, total salt, N, P, and K contents (P<0.01), indicating that these soil factors could significantly affect the contents of heavy metals carried by soil microplastics. This research demonstrated that the contents of soil microplastics are lower than other areas of the world, and they mainly come from industrial and agricultural activities of the Ebinur Lake Basin.

Keywords: occurrence characteristics; source analysis; soil microplastics; heavy metals; Ebinur Lake Basin

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1 Introduction

In 2018, the total global plastic production reached 360×10^6 t, and the wide use of plastic products was accompanied by the generation of large amount of plastic waste. From 1950 to 2015, the world's plastic waste reached about 6.3×10^9 t (Chae and An, 2018; Bradney et al., 2019; Ju et

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al., 2021). Although most plastics are durable and recyclable materials, only 6%–26% of plastic waste is recycled. Most of the rest ends up in landfills or is directly discarded into the environment (de Souza Machado et al., 2018; Windsor et al., 2019). Under ultraviolet radiation, weathering, and biological activities, large pieces of plastic garbage are gradually decomposed to form plastic fragments, particles, or fibers with particle sizes lower than 5 mm, i.e., microplastics (Qi et al., 2018).

As an emerging pollutant, microplastics have attracted the attention of scholars and the general public in recent years (Browne et al., 2011; Cole et al., 2013). Due to their light weight, small particle size, large quantity, and difficult degradation, microplastics are found in rivers, lakes, oceans, and even in drinking water and salt (Yan et al., 2019; Malankowska et al., 2021). Microplastics can exhibit diverse forms and complex chemical compositions. At present, common chemical types of microplastics include polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyamide (PA), and polyester (PES) (Free et al., 2014; Oni et al., 2020; Qi et al., 2020; Zhang et al., 2020). Microplastics have a certain hydrophobicity, which can cause the enrichment of microorganisms and pollutants on their surface. They can accumulate in microorganisms through feeding, changing biological metabolism of organisms, and producing biological effects such as immune responses, neurotoxicity, genotoxicity, and inflammatory reactions (Eerkes-Medrano et al., 2015; Xiong et al., 2019; Hernández-Sánchez et al., 2021). They can also be transferred from low to high trophic levels in food webs, thus affecting biodiversity, ecosystem services, and human health (Yang et al., 2015; Shen et al., 2020; Wong et al., 2020).

To date, the microplastic pollution of aquatic ecosystems, especially marine environments, has been widely studied. Global research on microplastics has mainly focused on the oceans (Costa and Barretta, 2015; Kooi et al., 2016; Taylor et al., 2016), polar glaciers (Obbard et al., 2014), and coastlines of continents (Browne, 2015). Microplastics have been found even in aquatic organisms far away from human settlements, such as deep-sea corals (Woodall et al., 2014). Compared with ocean studies, there are many reports on freshwater microplastics globally (Zhang et al., 2018; Lahive et al., 2019; Zhang et al., 2020). Among those, most studies on microplastics in rivers and lakes are from Europe, followed by North America and Asia. For example, Fischer et al. (2016) analyzed the contents of microplastics in 36 lakeshore sediment samples from Italy, and found the concentration of microplastics ranging from 268 to 3360 particles/kg. Vaughan et al. (2017) evaluated the concentration of microplastics in the sediments of small lakes and urban lakes in UK for the first time. The maximum concentration reached 25–30 particles/100 g dry sediments, and fibers and films were the most common microplastic types. Sruthy and Ramasamy (2017) studied microplastics in the Vembanad Lake in India. The abundance of microplastics in sediments ranged from 96 to 496 particles/m^2, with an average abundance of 253 (±26) particles/m^2. And low-density polyethylene was the main polymer component of microplastics.

Soil is one of the most valuable resources on Earth, and provides a series of important ecosystem functions and services to humans and other organisms. It provides the medium for plant growth, participates in biogeochemical cycles and carbon sequestration, and maintains soil biodiversity (Hü-Tsch et al., 2002; Waldrop et al., 2010; Mohanty et al., 2013). Due to increasing human activities, soil suffers from erosion, heavy metal pollution, compaction, and salinization (Arias-Estévez et al., 2008; Rosowiecka and Nawrocki, 2010). As an emerging pollutant, microplastics also threaten soil health, and may lead to land degradation. The pollution of soil with microplastics has attracted much attention in recent years (Andrady, 2011; Law and Thompson, 2014; Obbarb et al., 2014). It is estimated that the total amount of microplastics entering the soil environment every year is about 4–23 times that of the marine environment. In Europe and North America, more than 7×10^5 t of microplastics accumulate in the soil every year, which greatly exceeds the total weight of microplastics in the global ocean and surface water (93×10^3–236×10^3 t) (Andrady, 2017; Zhang et al., 2020). Soil has become a huge microplastic sink. Considering its core role in terrestrial ecosystems, it is imperative to study the impact of microplastics on terrestrial systems, especially the soil environment. At present, the main contents

of researches include: (1) the sources and migration of soil plastics and the basic characteristics of long-term storage in the soil; (2) the impacts of soil microorganisms on microplastics; and (3) the impacts of plastic pollution on the soil microbial community and enzyme activity, soil animals, crop production, and global terrestrial ecosystem function (He et al., 2018; Scheurer and Bigalke, 2018; Ju et al., 2021).

Here, we studied the Ebinur Lake Basin, an oasis in Xinjiang, Northwest China with rapid industrial and agricultural development, and investigated the occurrence characteristics, status, and sources of microplastics in the soil and their relationships with heavy metal pollutants. Our results may provide a scientific basis and reference for preventing and controlling microplastic pollutants in oasis soil in the Ebinur Lake Basin and other arid areas in Central Asia.

2 Materials and methods

The Ebinur Lake Basin is located in northwestern Xinjiang Uygur Autonomous Region, China (43°38″N–45°52″N and 79°53″E–85°02″E), and is surrounded by the Bortela Valley to the west, the Jinghe River proluvial fan to the south, and the Gobi desert to the east (Fig. 1; Abuduwaili et al., 2015; Yushanjiang et al., 2018). This basin covers an area of 50,621 km^2, including 24,317 km^2 of mountain area, 25,762 km^2 of plain area, and 542 km^2 of lake area. It has a typical temperate dry and early continental climate. There are 47 rivers in the basin, and its total surface runoff is 37.5×10^8 m^3/a. The total annual precipitation of the basin is 134.0×10^8 m^3/a, and mountainous areas account for 75% of the total precipitation (100.4×10^8 m^3/a). The total precipitation in plain areas is 33.6×10^8 m^3/a, accounting for 25% of the total precipitation. There are about 53 families, 191 genera, and 385 species of plants. The main vegetation types include *Haloxylon ammodendron* (C. A. Mey.) Bunge, *Populus euphratica* Oliv., *Populus tomentosa* Carr., *Populus alopecuroides* L., *Ulmus pumila* L., *Achnatherum splendens* (Trin.) Nevski, and *Phragmites australis* (Cav.). With the rapid development of industry and agriculture, urban construction, and transportation in recent years, heavy metals and other pollutants have increased in the soil of the basin, and microplastics have appeared (Zhang et al., 2018).

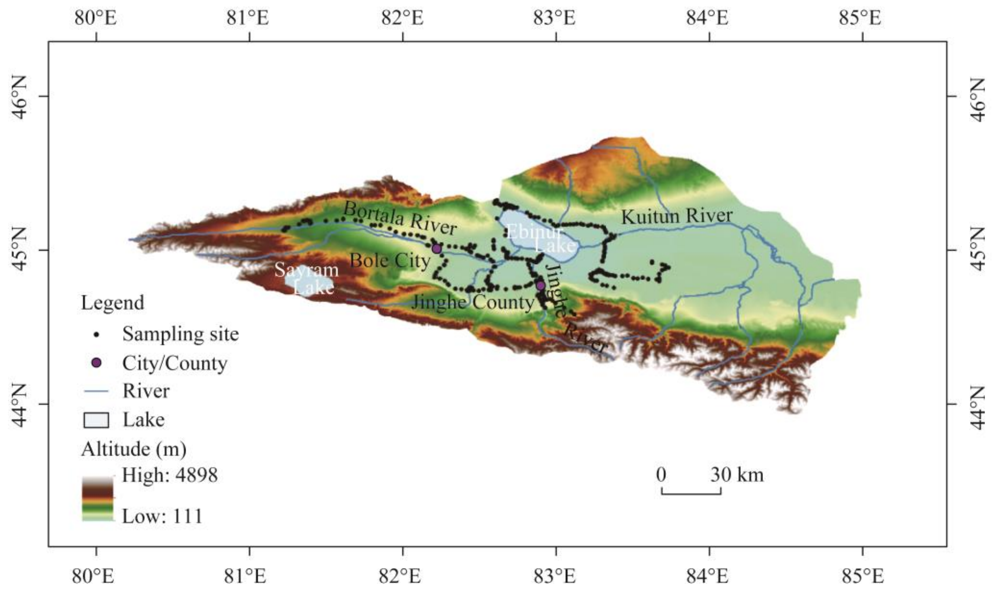

Fig. 1 Soil sampling sites in the Ebinur Lake Basin, Northwest China

2.1 Sampling and laboratory analyses

Sampling was performed in June 2021. On this date, there were few influencing factors such as wind-sand activities, agricultural activities, and precipitation. Then the grid method was used to

collect soil samples across the Ebinur Lake Basin. A total of 120 soil sampling sites were established, including 60 sites in farmland, 30 sites in woodland, and 30 sites in desert (Fig. 1). The sampling grid was 1 km, and a five-point sampling method was used for sampling. The collection steps were as follows: first, a stainless-steel sampling shovel was used to collect surface soil (0–5 cm). A total of 3 parallel samples were taken at each sampling point. After collecting soil samples, large stones and tree branches were removed. Samples were then stored in clean aluminum boxes, sealed with sealing film, placed into self-sealing bags, transported to the laboratory, and stored at 4°C in the dark until analysis.

The density flotation method with saturated zinc chloride ($ZnCl_2$) solution was used to separate and extract soil microplastics (Wang et al., 2016; Kang et al., 2020). The steps were as follows: 300 g of each soil sample was transferred to a white porcelain tray, and dried at 60°C in a vacuum drying oven. The dried soil was evenly mixed, and passed through the 5- and 2-mm stainless steel screens to remove large stones and branches retained on the two screens. The sieved soil sample was then evenly mixed, and 200 g was divided into three equal parts. Before the experiment, $ZnCl_2$ solution (ρ=1.6 g/cm^3) was filtered through a mixed cellulose ester membrane with a diameter of 47 mm and a pore diameter of 0.45 μm. Then, 50 g of sieved soil sample (n=3) was weighed into a 500-mL glass beaker, and 150 mL $ZnCl_2$ solution was added. This slurry was continuously stirred on an electrothermal constant temperature magnetic stirrer for 30 min, followed by a 12-h sedimentation step. After solid-liquid stratification, the supernatant was filtered through a vacuum suction filter. The filter was a nitrocellulose membrane (Whatman AE 98) with a diameter of 47 mm and a pore diameter of 0.45 μm.

The inner wall of the filter was rinsed repeatedly with deionized water, and the flushing solution was also filtered. The filter membrane containing microplastics was transferred into a 60-mm glass Petri dish with stainless steel tweezers for storage and digestion to remove the residual organic matter of the sample for subsequent observation, selection, and treatment. Microplastics were picked with toothless stainless-steel tweezers and anatomical needles under a stereomicroscope (Olympus SZ61, Olympus Corporation, Tokyo, Japan). Then, we placed the selected potential microplastic particles on a Whatman membrane, and marked it. We classified samples according to their color and morphological characteristics, and recorded in a spreadsheet. A single layer picture of the sample was taken, and the size of potential microplastic particles was measured as the maximum diameter. A Fourier micro infrared spectrometer (Perkin Elmer spotlight 400, Perkin Elmer GmbH, Waltham, USA) was used to identify the polymer composition, and characterize the functional groups of particles with a particle size of 0–5000 μm. Then, the spectrum was compared with the standard spectrum library. Samples corresponding to the spectrum with a matching degree of 60% or more were considered microplastic, and their composition was determined.

Soil analyses followed "The Method of Soil Agrochemical Analysis" by Lu et al. (2002). Soil physical and chemical variables were determined as follows: moisture content was determined with the drying method, pH with the glass electrode method, and electric conductance (EC) with an electrode (HQ1130, HACH Co., Ltd., Colorado, USA). The total salt content was determined with a gravimetric method, potassium content with ammonium acetate ($NH_4CH_3CO_2$) extraction flame spectrophotometry, and phosphorus content with sodium bicarbonate extraction molybdenum antimony anti-colorimetry. The potassium content was determined with the nitrogen alkali hydrolysis diffusion method (Lu, 2002). Heavy metals of Cu, Ni, Cd, Pb, Cr, Mn, and Co in microplastics were analyzed as follows: first, we placed 1 g of microplastic particles into a centrifuge tube, then added 1 mL 2% HNO_3, and used an ultrasonic instrument for auxiliary digestion. After digestion, the contents of seven heavy metals were determined by inductively coupled plasma mass spectrometry (ICP-MS, Jena analytical instruments Co., Ltd., Germany). During analyses, the blank tests were performed together with soil metal calibrations with standards from the Standard Material of China. To verify the accuracy of these measurements, we measured 15% of the soil samples in duplicate. The accuracy or precision of the measurements was determined to be 93.56%–97.98%. Prior to analysis, we soaked glassware in 5% HNO_3 for 24

h, rinsed with ultrapure water, and dried. All reagents were of analytical grade, and were used without further purification. All solutions were prepared with Milli-Q water.

2.2 Single-factor pollution index

The single-factor pollution index is widely used to evaluate the concentration characteristics of pollutants such as heavy metals and organic pollutants in soil (Abuduwaili et al., 2015; Zhang et al., 2018). The formula is as below:

$$P_i = \frac{C_i}{S_i}, \quad (1)$$

where P_i is the environmental quality index of pollutant i in soil; C_i is the measured concentration of pollutants (n/kg); and S_i is the evaluation standard of pollutants (n/kg). In this study, we chose the average value of microplastics in the Ebinur Lake Basin. P_i values ranged from 0.0 to 0.7, indicating no pollution; P_i values ranged from 0.7 to 1.0, indicating slight pollution; and P_i values were higher than 1.0, indicating pollution (Zhang et al., 2016).

2.3 Random forest regression analysis

Random forest is a classifier integration algorithm based on decision trees proposed by Breiman (2001). Several samples are randomly selected from the original sample set by bootstrap resampling to generate new sample sets. Then, we constructed the decision tree based on the new sample sets to form the random forest. For regression analysis, the model takes the average value of N cart decision trees trained according to the weighted mean as the final prediction result (Li, 2013; Sihag et al., 2019). Compared with other algorithms, the advantages of the random forest model are: (1) no preprocessing of data, no requirements regarding data type and distribution, and strong robustness to noise and outliers; (2) the decision tree can be generated in parallel without pruning; and (3) the prediction result has high precision, and prevents the phenomenon of data overfitting (Antipov and Pokryshevskaya, 2012). The stochastic forest model is flexible and easy to understand. It has been widely used in many fields in recent years due to excellent properties.

Here, we used the random forest tool package in the R software to build random forest regression models. The mean square standard error %IncMSE was used to evaluate the influence of each prediction variable on the abundance of microplastics in farmland. The model's parameters, i.e., mtry, nTree, and nodesize were set before analysis. Mtry represents the number of sample predictors at each split node (Zhang et al., 2021). Generally, one-third of the number of predictor variables is used for regression analysis. NTree represents the number of growth trees and nodesize of the minimum number of decision tree nodes. Default values were adopted in the model. Therefore, the final parameters were set as: mtry=4, nTree=500, and nodesize=5. The final result of the model evaluation is represented by %IncMSE. The larger the %IncMSE, the higher the correlation between predicted and dependent variables.

This study considered various factors directly related to the occurrence of microplastics in soil, such as the level of economic development, industrial and living sources, population, agricultural use of plastics, and soil physical and chemical properties. Twelve predictive variables were selected, i.e., gross domestic product (GDP), industrial GDP, population, agricultural use of plastic film, domestic sewage discharge, industrial sewage discharge, chemical oxygen demand of industrial wastewater, cotton sowing area, and proportions of sand, silt, and clay. Soil particle sizes were measured with a soil particle size analyzer. Other data were obtained from Bole Municipal Bureau of Statistics, Jinghe County Bureau of Statistics, Bortala Mongolian Autonomous Prefecture Bureau of Statistics and Xinjiang Statistical Yearbook (SBXAR, 2020).

2.4 Data analysis

The abundance of soil microplastics was expressed as n/kg, and the content as mg/kg. The data were plotted using the software Origin v.9.0 (OriginLab Corporation, Northampton, MA, USA). SPSS v.22.0 (SPSS Inc., Chicago, IL, USA) was used to test the significance of differences in the abundance of microplastics in the sampling area (one-way analysis of variance (ANOVA)), and a significance level of P<0.05 was adopted.

3 Results

3.1 Distribution and pollution degree of microplastics in soil

Using relevant analytical methods, we divided the microplastics into five types in shape, i.e., film, fragment, fiber, foam, and particle (Fig. 2). Overall, the proportion of microplastics diminished in the following order: film (54.25%)>fiber (18.56%)>particle (15.07%)>fragment (8.66%)>foam (3.46%). Further, five colors of soil microplastics were found, i.e., white, black, green, transparent, and yellow. Among all microplastic particles, white accounted for the largest proportion (52.93%), followed by green (24.15%), black (12.17%), transparent (7.16%), and yellow (3.59%; Fig. 3). The film was white (41.32%), and most fibers were also white (58.86%). Most particles (36.21%) and fragments (37.45%) were green. Yellow (27.90%) accounted for the largest proportion of foam. Microplastics in farmland (54.61%) and woodland (39.41%) were mainly white. Desert had mainly black microplastics (25.31%).

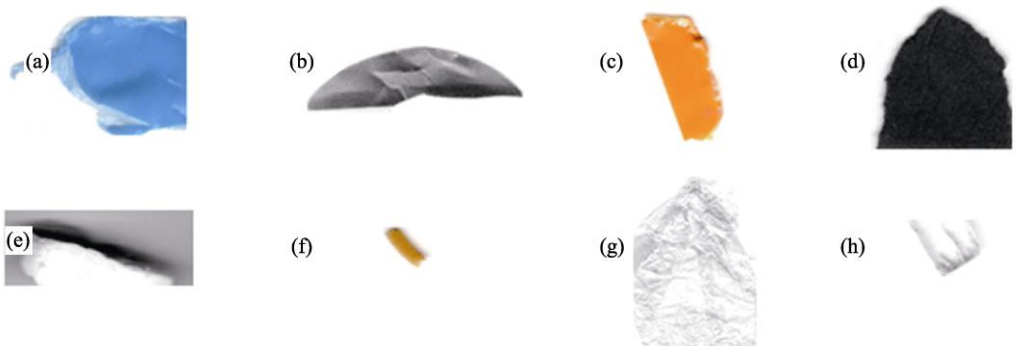

Fig. 2 Morphology of soil microplastics in the Ebinur Lake Basin. (a), film; (b), fragment; (c), fiber; (d), fragment; (e), foam; (f), particle; (g), film; (h), particle.

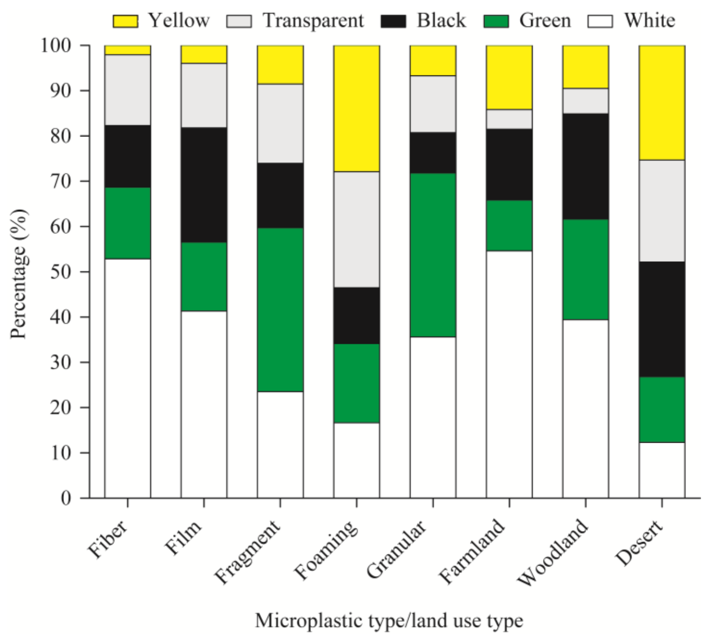

Fig. 3 Soil microplastic colors in the Ebinur Lake Basin

In this research, the particle sizes of microplastics were divided into five classes, i.e., 0–100, 100–500, 500–1000, 1000–2000, and 2000–5000 μm. As shown in Figure 4, the proportion of microplastic size classes in 120 soil samples decreased in the following order: 1000–2000 μm

(40.88%)>500–1000 μm (26.75%)>2000–5000 μm (12.30%)>100–500 μm (12.92%)>0–100 μm (7.15%). The largest proportions of particle sizes of film, fiber, particles, fragments, and foam were 39.41%, 45.32%, 33.21%, 58.32%, and 35.21% for 1000–2000 μm, respectively. The particle size classes with the largest proportions in farmland, woodland, and desert were 2000–5000 μm (29.58%), 1000–2000 μm (50.16%), and 1000–2000 μm (36.32%), respectively.

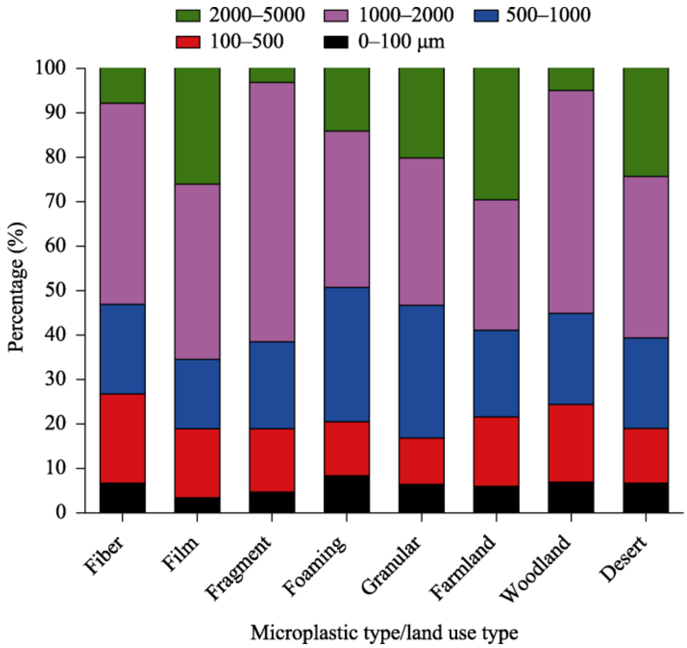

Fig. 4 Particle size classification of soil microplastics in the Ebinur Lake Basin

In this study, microplastic pollutants were analyzed in 120 soil samples, and an average content of 36.15 (±3.27) mg/kg was found. The contents of microplastics across sampling points ranged from 3.89 (±1.64) to 89.25 (±2.98) mg/kg (Table 1). The site with the highest content of microplastics was located in farmland near the Bortala River estuary in western part of the Ebinur Lake, followed by the Bole City. The average content of microplastics in farmland was 45.13 (±2.30) mg/kg, followed by woodland (34.17 (±3.21) mg/kg), and finally, desert (29.15 (±1.89) mg/kg). The film content was 18.62 (±2.34) mg/kg, the fiber content 15.16 (±1.29) mg/kg, the particle content 34.45 (±2.45) mg/kg, the fragment content 20.16 (±2.54) mg/kg, and the foaming content 30.15 (±3.21) mg/kg. One-way ANOVA showed significant differences in the distribution of microplastics among species, and there were also significant differences among three land use types (Table 1).

Table 1 Statistical characteristics of soil microplastics in the Ebinur Lake Basin

Microplastic type /land use type	Sample number	Abundance (n/m^2)	Average (mg/kg)	Range (mg/kg)	Median (mg/kg)	Proportion (%)
Fiber	120	21.51 ± 2.14^a	15.16 ± 1.29^a	0.86–68.56	14.13±1.89	18.56
Film	120	15.15 ± 2.01^b	18.62 ± 2.34^b	0.49–32.17	15.62±3.23	54.25
Fragment	120	26.54 ± 1.24^c	20.16 ± 2.54^c	1.25–40.56	22.54±3.54	8.66
Foam	120	35.74 ± 1.65^d	30.15 ± 3.21^d	3.25–50.14	26.23±4.23	3.46
Granular	120	30.55 ± 2.35^e	34.45 ± 2.45^e	6.61–20.19	35.41±2.61	15.07
Farmland	60	46.54 ± 1.58^f	45.13 ± 2.3^f	2.91–68.56	28.27±4.23	59.67
Woodland	30	36.25 ± 1.89^g	34.17 ± 3.21^g	3.65–50.14	36.16±2.32	20.15
Desert	30	35.15 ± 2.14^h	29.15 ± 1.89^h	2.64–40.27	33.32±2.52	20.18

Note: Different lowercase letters within the same column indicate significant differences among different microplastic types and land use types at $P<0.05$ level.

The single-factor pollution index showed that 76.50% of farmland samples, 55.47% of woodland samples, and 34.25% of desert samples were polluted (P_i>1.0). Thus, the pollution degree of different land use types diminished in the order of farmland>woodland>desert. The shape characteristics of microplastics were different among sampling sites. For example, the sampling sites B-1 and B-11 only had fiber and film, while microplastics of five shapes and types were found at B-25 and B-26 sites, and B-57–59 sites had mainly fiber, fragments, and particles. Thin film and fibrous microplastics were detected at all sites in this study, accounting for 15.23%–72.41%.

3.2 Composition of soil microplastics

The microplastic contents of sampling sites near towns in the Ebinur Lake Basin were significantly higher than those in other areas, and the microplastic contents of downwind sampling sites in the south were higher than those in upwind settlements in the north. The contents of microplastics in dustfall near the estuaries, such as the Bole City and Jinghe County, were significantly higher than those in other sites. The contents of microplastics in woodland and desert were the lowest. This result showed that microplastics in soil samples near cities and towns mainly came from the urban discharge of plastic pollutants. Microplastics in the atmospheric dust near farmland mainly came from weathering, debris, and near the ground settlement of chemical fertilizer, pesticide packaging materials, and agricultural plastic film coverage.

The components of five types of soil microplastics were determined by infrared spectrum analysis in our study. The first type of soil microplastics was polyethylene terephthalate (PET; Fig. 5a and b), which has a typical C=O functional group at wave 1700, C–O at wave 1500 cm^{-1}, and P-disubstituted benzene at wave 800–860 cm^{-1} (Fig. 5a). The second type was PP, which has a typical C=C functional group at wave 1630 cm^{-1}, -CH_3 at wave 1570 cm^{-1}, and R-CH=CH_2 at wave 900–1000 cm^{-1} (Fig. 5b). The third type was PC, which has a typical monosubstituted benzene functional group at waves 690–710 and 750–770 cm^{-1}, p-disubstituted benzene at wave

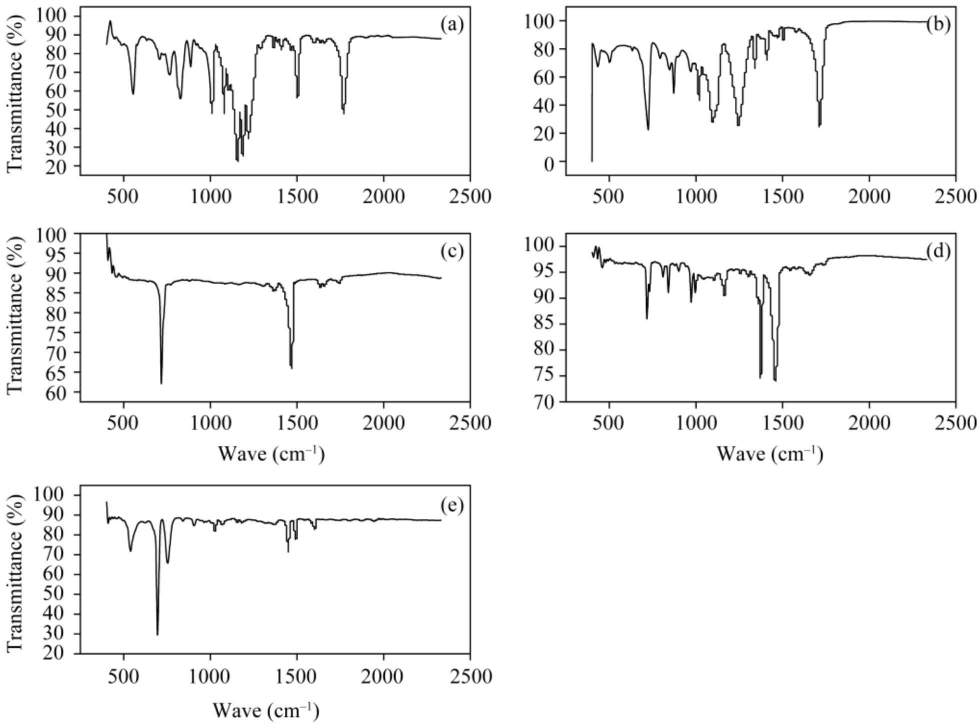

Fig. 5 FTIR (Fourier transform infrared) spectra of soil microplastics in the Ebinur Lake Basin. (a), polyethylene terephthalate (PET) type; (b), polypropylene (PP) type; (c), polycarbonate (PC) type; (d) polyethylene (PE) type; (e) polystyrene (PS) type.

800–860 cm^{-1}, =C–H, O-H at wave >3000 cm^{-1}, and C=O at wave 1700 cm^{-1} (Fig. 5c). The fourth type was PE, with a typical C=C functional group at wave 1550 cm^{-1} and C-O at wave 1000 cm^{-1} (Fig. 5d). The fifth type was PS, which has a typical C=C functional group at wave 1670 cm^{-1}, and monosubstituted benzene at waves 690–710 and 750–770 cm^{-1} (Fig. 5e).

3.3 Source identification of soil microplastics

There are many factors affecting the occurrence of microplastics in soil. This study used the random forest regression model to analyze the entire Ebinur Lake Basin. An importance ranking analysis of the possible influencing factors was carried out. The results show that the contents of soil microplastics in the Ebinur Lake Basin were closely related to the use of agricultural plastic film, total industrial output, and population (Fig. 6). The main land use type in the basin was farmland. Most sample sites in this study located in farmland. Therefore, agricultural activities were the most important factor affecting the soil in this area, followed by industrial activities and domestic emissions. The importance ranking results of random forest variables indicated, to a certain extent, the source of soil microplastics. Activities such as industrial and agricultural production and the discharge of domestic waste plastics were related to soil microplastic pollution. The use of agricultural plastic film was the most important factor in soil pollution.

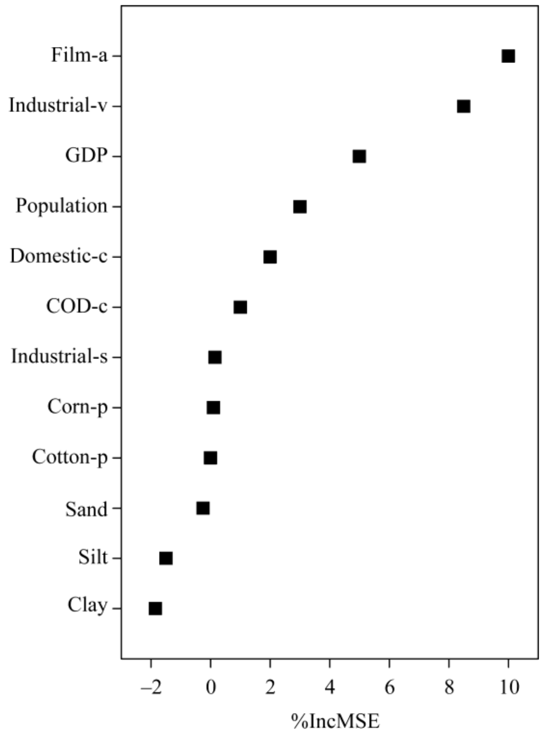

Fig. 6 Importance ranking of random forest variables. Film-a, agricultural film use; GDP, regional gross domestic product; Industrial-v, industrial GDP; Domestic-c, domestic sewage discharge; COD-c, chemical oxygen demand of industrial wastewater; Industrial-s, industrial wastewater discharge; Corn-p, corn sown area; Cotton-p, cotton sown area; %IncMSE, increase in mean squared error.

In this study, the main components of film microplastics in the soil of the Ebinur Lake Basin were PE and PP. We speculated that broken waterproof film layers of daily life plastic products, such as food packaging bags, and woven bags for industrial and agricultural production, were the main source of film microplastics. In our research, the main components of fragment microplastics were PP and PE that mainly came from broken fragments of large-scale plastic industrial packaging materials or woven plastic bags, as the edges had regular shapes. In the Ebinur Lake Basin, the decomposition of woven bags of chemical fertilizer and cement probably

was the main source. The main component of foam and granule was PS, with mostly lamellar and columnar shapes, and the main colors were white and colorless. The main component of fiber was PET, mostly black and yellow, probably coming from the sewage discharge after washing of fabrics in clothing and textile industries near cities and towns. In addition, fishing gear, atmospheric deposition, and surface runoff are also potential sources of plastic fibers. During the sampling period, fragments of foam, packaging bags, chemical bags, plastic bottles, and food packaging paper were found in towns, farmland, and woodland, indicating that microplastic pollutants in the Ebinur Lake Basin mainly come from industrial and agricultural production, and domestic sources.

4 Discussion

4.1 Soil microplastic pollution in the Ebinur Lake Basin

Compared with previous studies (Table 2), the content of microplastics in the studied soil was relatively low, and the soil environment was in good condition. Abundances of soil microplastics in our study were much lower than those of industrial land in some areas of Australia (Yang et al., 2021), cultivated land in Iran (Rezaei et al., 2019), cultivated land in Chile (Corradini et al., 2019), and green land in the United States (Helcoski et al., 2020) and Mexico (Huerta et al., 2017). Soil microplastic contents in the Ebinur Lake Basin were also lower than those of cultivated land and tidal flats in some provinces of China, such as cultivated land in the provinces of Yunnan (Zhang and Liu, 2018), Zhejiang (Zhou et al., 2020), Heilongjiang (Zhang et al., 2020), Shaanxi (Ding et al., 2020), Hubei (Chen et al., 2020), Shandong (Zhou et al., 2016), Hebei (Lv et al., 2019), and Guangxi Zhuang Autonomous Region (Zhang et al., 2020). However, microplastic contents were higher than those in the Mexican green space and cultivated land in the Shanghai City (Huerta et al., 2017; Liu et al., 2018).

Table 2 Abundance of soil microplastics in China and worldwide

Region/land use type	Component	Shape	Particle size	Abundance (n/kg)	Reference
Australia/industrial land	PE, PVC, PS	/	<1 mm	300–67,500	Yang et al. (2021)
Iran/cultivated land	PE	Fragment	40–740 μm	67–400	Rezaei et al. (2019)
Chile/cultivated land	/	Fiber	<4 mm	600–10,400	Corradini et al. (2019)
Germany/cultivated land	PE, PS	Debris, film	<5 mm	0.34±0.36	Piehl et al. (2018)
USA/green space	PE, PS	Fiber	<5 mm	334–3068	Helcoski et al. (2020)
Switzerland/beach	PE, PP	/	<2 mm	0.0–55.5	Scheurer and Bigalke (2018)
Mexico/green space	PE	Particle	10–50 μm	870±190	Huerta et al. (2017)
Yunnan/cultivated land	/	Fiber	1.00–0.05 mm	7100–42,960	Zhang and Liu (2018)
Zhejiang/cultivated land	PE, PP	Debris, fiber	<5 mm	0–2760	Zhou et al. (2020)
Heilongjiang/cultivated land	PE	Film	<5 mm	0–800	Zhang et al. (2020a)
Guangxi/cultivated land	PP, PE, PET	Debris, fiber	<5 mm	5.0–549.9	Zhang et al. (2020b)
Shaanxi/cultivated land	PS, PE, PP	Fiber, particle	<5 mm	1430–3410	Ding et al. (2020)
Hubei/cultivated land	PA, PP	Fiber, particle	<0.2 mm	320–12,560	Chen et al. (2020)
Shandong/beach	PE, PP, PS	Foam, debris	<5 mm	1.3–14,712.5	Zhou et al. (2016)
Hebei/beach	/	Particle, fragment	1.56±0.63 mm	0–634	Lv et al. (2019)
Shanghai/cultivated land	PP, PE	Fiber	<1 mm	10.3±0.2	Liu et al. (2018)
Ebinur Lake Basin	PP, PE, PVC	Foam, debris, fiber, film	<5 mm	36.15	This research

Note: PVC, polyvinyl chloride; PET, polyethylene terephthalate; PP, polypropylene; PC, polycarbonate; PE, polyethylene; PS, polystyrene.

Our study showed that the main microplastic components in the Ebinur Lake Basin were PE,

PVC, and PS, which is consistent with other studies (Liu et al., 2018; Yang et al., 2021). We found many types of microplastics in the environment, such as fiber, film, foam, and particles. Fiber-based microplastics were found to be dominant in soil samples. However, this study found that the total proportion of film microplastics in the soil of the Ebinur Lake Basin was higher than that of fiber microplastics because the debris had a lower specific surface volume and migrated more easily into the soil (Yang et al., 2021). Granular, foam, and debris microplastics accounted for the smallest proportion of all soil microplastics in this study (3.46%–15.07%). This corresponded well with Corradini et al. (2019), who reported microplastic accumulation in agricultural soil, and that debris accounted for a large proportion. The possible reason for this is that granular microplastics are mainly derived from the decomposition of hard plastics, which takes a long time. The color distribution characteristics of microplastics are obviously different from the wide sources of microplastics and the interference of human activities. The colored microplastics in domestic sewage (e.g., from laundry) discharged from residential areas, and sewage treatment plants are ingested by soil organisms, then damaging their health (Zhang et al., 2020).

This study provides a preliminary analysis of the spatial distribution of different types of microplastics in the soil of the Ebinur Lake Basin. There were many farms near the Bole City and Jinghe County, and the proportion of thin-film microplastics was the highest in these regions. Therefore, we speculated that the main reason for the high abundance of microplastics in these two sites is the crushing and decomposition of agricultural plastic film and domestic plastic waste. In addition, the Bortala River estuary had a low current velocity, and the sediments deposited near the sampled river bend may carry microplastic particles, resulting in a relatively large abundance of microplastics. Although there were plastic processing plants and sewage treatment plants near the Bole City and Jinghe County, the population density was high, and film and fiber microplastics at these sampling sites accounted for 50% of the total microplastics. Therefore, we speculated that the main origin of these microplastics was clothes particles from washing and discarded plastic garbage bags. There were differences in the content of soil microplastics near the Bole City and Jinghe County, and the content was often higher than those of other sampling sites. The reason for this may attributed to the dense population and garbage near the town, resulting in increased microplastic pollution. It is also possible that sewage treatment plants and plastic processing plants represented the increased abundance of microplastics.

4.2 Relationships between soil microplastics and adsorbed metals

The contents of heavy metals adsorbed by collected soil microplastics were analyzed. Then the correlations among the abundance, contents, color, carried heavy metals of different types of microplastics, and soil physical and chemical properties were analyzed to assess the mobility of metals and influencing factors. The abundance and content of microplastics had no significant correlation with soil pH, EC, and total salt content (Table 3). However, there was a significant negative correlation with soil moisture and water volume ($P<0.01$), and the correlation coefficients were 0.85 between microplastic abundance and soil moisture, 0.45 between microplastic abundance and precipitation, 0.42 between microplastic content and soil moisture, and 0.35 between microplastic content and precipitation, indicating that high soil moisture or rainfall scouring caused the migration of microplastics, and the increase of soil moisture resulted in the migration and export of microplastics, and reduced their abundance (Zhang et al., 2020). The color of microplastics had no significant correlation with pH, EC, total salt content, nitrogen, phosphorus, potassium, and precipitation, indicating that these soil variables do not affect the color of microplastics. The abundance and content of soil microplastics were significantly correlated with the contents of N, P, and K. The correlation coefficients were 0.56 between microplastic abundance and N, 0.69 between microplastic abundance and P, 0.65 between microplastic abundance and K, 0.52 between microplastic content and N, 0.51 between microplastic content and P, and 0.54 between microplastic content and K ($P<0.01$), indicating that microplastics changed significantly with agricultural fertilization activities. The seven heavy

metals extracted from microplastics in our study showed a significant positive correlation with soil pH, EC, and total salt, N, P, and K contents (P<0.01), indicating that these soil variables significantly affected the content of heavy metals carried by microplastics. This result implied that the heavy metals on the surface of soil microplastics mainly came from soil fertilization, and were affected by pH, EC, and the contents of soil N, P, K and total salt. Previous studies have shown that the contents and morphological changes of heavy metals in soil were significantly related to these factors (Zhang et al., 2022). The seven heavy metals were significantly negatively correlated with soil moisture and precipitation, and the correlation coefficients were 0.31 between Cu and soil moisture, 0.29 for Ni, 0.33 for Cd, 0.26 for Pb, 0.19 for Cr, 0.42 for Mn, and 0.33 for Co (P<0.01).

Table 3 Correlation of microplastic abundance and heavy metal content with soil physical and chemical properties

Soil variable	Abundance	Content	Color	Cu	Ni	Cd	Pb	Cr	Mn	Co
pH	0.49	0.37	0.64	0.55**	0.56**	0.64**	0.68**	0.61**	0.75**	0.80**
EC	0.41	0.50	0.31	0.56**	0.52**	0.60**	0.58**	0.53**	0.56**	0.61**
Total salt	0.42	0.36	0.28	0.51**	0.61**	0.62**	0.57**	0.53**	0.52**	0.49*
Soil moisture	–0.85**	–0.42**	0.41	–0.31*	–0.29*	–0.33*	–0.26*	–0.19*	–0.42*	–0.33*
N	0.56**	0.52**	0.54*	0.58**	0.52**	0.49*	0.56**	0.57**	0.52**	0.54**
P	0.69**	0.51**	0.45	0.53**	0.56**	0.45*	0.58**	0.61**	0.49*	0.64**
K	0.65**	0.54**	0.49	0.51**	0.53**	0.54**	0.62**	0.56**	0.48*	0.51**
Precipitation	–0.45*	–0.35*	–0.27	–0.16*	–0.11*	–0.21*	–0.18*	–0.17*	–0.35*	–0.44*

Note: EC, electric conductivity; N, nitrogen; P, phosphorous; K, potassium. *, P<0.05 level; **, P<0.01 level.

The lack of unified method for studying soil microplastics results in the difficulty to assess the soil safety. Therefore, it is necessary to establish standard methods for collecting, separating, and analyzing various types of microplastics in soil samples in the future (Rillig et al., 2017). Accurate, simple, and efficient analysis technology will be the basis for an in-depth understanding of soil microplastic pollution (Koelmans et al., 2020; Yang et al., 2021). At present, the land use type most studied regarding soil microplastic pollution is cultivated land, and the existing data are insufficient to analyze the pollution of soil microplastics in China or worldwide (Zhang et al., 2020).

In previous studies, microplastics were often regarded as a simple polymer. In fact, microplastics may contain many chemical additives (such as plasticizers and flame retardants) (Eriksen et al., 2013). To date, most studies have been done under laboratory conditions, and the concentrations of microplastics were high, leading to a certain incompatibility between simulated and real concentrations in the natural environment. Therefore, it is necessary to explore whether and how microplastic pollution affects soil animals, microorganisms, and plants *in situ* in the future, which is also essential to deeply understand the environmental effects of microplastics (Weithmann et al., 2018; Zhang et al., 2020).

5 Conclusions

Random forest prediction in this study confirmed that microplastic contents were closely related to the use of agricultural plastic film, total industrial output, and population. Activities such as industrial and agricultural production, and the discharge of domestic waste plastics were related to soil microplastic pollution, and the use of agricultural plastic film was the most important factor for soil pollution in this area. Compared with previous studies, the microplastic content in the soil of the Ebinur Lake Basin was relatively low, and the soil was in good condition. Future research should focus on the analysis of pollution degree of microplastics in different land use types, and

explore the sources of microplastics, which will help managers take measures to control soil microplastic pollution.

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References

Abuduwaili J, Zhang Z Y, Jiang F Q. 2015. Assessment of the distribution, sources and potential ecological risk of heavy metals in the dry surface sediment of Aibi Lake in northwest China. PLoS ONE, 10(3): e0120001, doi: 10.1371/journal.pone.0120001.

Andrady A L. 2011. Microplastics in the marine environment. Marine Pollution Bulletin, 62(8): 1596–1605.

Andrady A L. 2017. The plastic in microplastics: A review. Marine Pollution Bulletin, 119(1): 12–22.

Antipov E A, Pokryshevskaya E B. 2012. Mass appraisal of residential apartments: An application of random forest for valuation and a CART-based approach for model diagnostics. Expert Systems with Applications, 39(2): 1772–1778.

Arias-Estévez M, López-Periago E, Martínez-Carballo E, et al. 2008. The mobility and degradation of pesticides in soils and the pollution of groundwater resources. Agriculture, Ecosystems and Environment, 123(4): 247–260.

Bradney L, Wijesekara H, Palansooriya K N, et al. 2019. Particulate plastics as a vector for toxic trace-element uptake by aquatic and terrestrial organisms and human health risk. Environment International, 131: 104937, doi: 10.1016/j.envint.2019.104937.

Browne M A, Crump P, Niven S J, et al. 2011. Accumulation of microplastic on shorelines worldwide: Sources and sinks. Environmental Science and Technology, 45(21): 9175–9179.

Browne M A. 2015. Sources and pathways of microplastics to habitats. Marine Anthropogenic Litter, 3(9): 229–244.

Chae Y, An Y J. 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. Environmental Pollution, 240: 387–395.

Chen Y, Leng Y, Liu X, et al. 2020. Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. Environmental Pollution, 257: 113–119.

Cole M, Lindeque P, Fileman E, et al. 2013. Microplastic ingestion by zooplankton. Environmental Science and Technology, 47(12): 6646–6655.

Corradini F, Meza P, Eguiluz R, et al. 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Science of the Total Environment, 671: 411–420.

Costa M F, Barletta M. 2015. Microplastics in coastal and marine environments of the western tropical and sub-tropical Atlantic Ocean. Environmental Science: Processes and Impacts, 17(11): 1868–1879.

de Souza Machado A A, Lau C W, Till J, et al. 2018. Impacts of microplastics on the soil biophysical environment. Environmental Science and Technology, 52(17): 9656–9665.

Ding L, Zhang S, Wang X, et al. 2020. The occurrence and distribution characteristics of microplastics in the agricultural soils of Shaanxi Province, in northwestern China. Science of the Total Environment, 720: 137–145.

Eerkes-Medrano D, Thompson R C, Aldridge D C. 2015. Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Research, 75: 63–82.

Eriksen M, Mason S, Wilson S, et al. 2013. Microplastic pollution in the surface waters of the Laurentian Great Lakes. Marine Pollution Bulletin, 77(1–2): 177–182.

Fischer E K, Paglialonga L, Czech E, et al. 2016. Microplastic pollution in lakes and lake shoreline sediments–a case study on Lake Bolsena and Lake Chiusi (Central Italy). Environmental Pollution, 213: 648–657.

Free C M, Jensen O P, Mason S A, et al. 2014. High-levels of microplastic pollution in a large, remote, mountain lake. Marine Pollution Bulletin, 85(1): 156–163.

He D, Luo Y, Lu S, et al. 2018. Microplastics in soils: analytical methods, pollution characteristics and ecological risks. TrAC Trends in Analytical Chemistry, 109: 163–172.

Helcoski R, Yonkos L T, Sanchez A, et al. 2020. Wetland soil microplastics are negatively related to vegetation cover and stem density. Environmental Pollution, 256: 113–119.

Hernández-Sánchez C, González-Sálamo J, Ortega-Zamora C, et al. 2021. Microplastics: an emerging and challenging research field. Current Analytical Chemistry, 17(7): 894–901.

Huerta L E, Mendoza V J, Ku Q V, et al. 2017. Field evidence for transfer of plastic debris along a terrestrial food chain.

Scientific Reports, 7: 14071, doi: 10.1038/s41598-017-14588-2.

Hütsch B W, Augustin J, Merbach W. 2002. Plant rhizodeposition–an important source for carbon turnover in soils. Journal of Plant Nutrition and Soil Science, 165(4): 397–407.

Ju Z C, Jin D C, Deng Y. 2021. The interaction between plastics and microorganisms in soil and their ecological effects. China Environmental Science, 41(5): 2352–2361. (in Chinese)

Kang P, Ji B, Zhao Y, et al. 2020. How can we trace microplastics in wastewater treatment plants: A review of the current knowledge on their analysis approaches. Science of the Total Environment, 745(2): 140–149.

Koelmans A A, Redondo-Hasselerharm P E, Mohamed Nor N H, et al. 2020. Solving the nonalignment of methods and approaches used in microplastic research to consistently characterize risk. Environmental Science and Technology, 54(19): 12307–12315.

Kooi M, Reisser J, Slat B, et al. 2016. The effect of particle properties on the depth profile of buoyant plastics in the ocean. Scientific Reports, 6: 33882, doi: 10.1038/srep33882.

Lahive E, Walton A, Horton A A, et al. 2019. Microplastic particles reduce reproduction in the terrestrial worm *Enchytraeus crypticus* in a soil exposure. Environmental Pollution, 255: 113–118.

Law K L, Thompson R C. 2014. Microplastics in the seas. Science, 345(3): 144–145.

Li X. 2013. Using "random forest" for classification and regression. Chinese Journal of Applied Entomology, 50(4): 1190–1197. (in Chinese)

Liu M, Lu S, Song Y, et al. 2018. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. Environmental Pollution, 242: 855–862.

Lu R K. 2002. Soil Agrochemical Analysis Methods. Beijing: China Agricultural Science and Technology Press, 456–475. (in Chinese)

Lv W, Zhou W, Lu S, et al. 2019. Microplastic pollution in rice-fish co-culture system: A report of three farmland stations in Shanghai, China. Science of the Total Environment, 652: 1209–1218.

Malankowska M, Echaide-Gorriz C, Coronas J. 2021. Microplastics in marine environment: a review on sources, classification, and potential remediation by membrane technology. Environmental Science: Water Research and Technology, 7(2): 243–258.

Mohanty M, Sinha N K, Reddy K S, et al. 2013. How important is the quality of organic amendments in relation to mineral N availability in soils?. Agricultural Research, 2(2): 99–110.

Obbard R W, Sadri S, Wong Y Q, et al. 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future, 2(6): 315–320.

Oni B A, Ayeni A O, Agboola O, et al. 2020. Comparing microplastics contaminants in (dry and raining) seasons for Ox-Bow Lake in Yenagoa, Nigeria. Ecotoxicology and Environmental Safety, 198: 110–118.

Piehl S, Leibner A, Löder M G, et al. 2018. Identification and quantification of macro- and microplastics on an agricultural farmland. Scientific Reports, 8: 17950, doi: 10.1038/s41598-018-36172-y.

Qi R, Jones D L, Li Z, et al. 2020. Behavior of microplastics and plastic film residues in the soil environment: A critical review. Science of the Total Environment, 703: 134–142.

Qi Y, Yang X, Pelaez A M, et al. 2018. Macro- and micro-plastics in soil-plant system: effects of plastic mulch film residues on wheat (*Triticum aestivum*) growth. Science of the Total Environment, 645: 1048–1056.

Rezaei M, Riksen M J, Sirjani E, et al. 2019. Wind erosion as a driver for transport of light density microplastics. Science of the Total Environment, 669: 273–281.

Rillig M C, Ziersch L, Hempel S. 2017. Microplastic transport in soil by earthworms. Scientific Reports, 7: 1362, doi: 10.1038/s41598-017-01594-7.

Rosowiecka O, Nawrocki J. 2010. Assessment of soils pollution extent in surroundings of ironworks based on magnetic analysis. Studia Geophysica and Geodaetica, 54(1): 185–194.

Scheurer M, Bigalke M. 2018. Microplastics in Swiss floodplain soils. Environmental Science and Technology, 52(6): 3591–3598.

Shen M, Song B, Zhu Y, et al. 2020. Removal of microplastics via drinking water treatment: Current knowledge and future directions. Chemosphere, 251: 126–132.

Sihag P, Karimi S M, Angelaki A. 2019. Random forest, M5P and regression analysis to estimate the field unsaturated hydraulic conductivity. Applied Water Science, 9(5): 129, doi: 10.1007/s13201-019-1007-8.

Sruthy S, Ramasamy E V. 2017. Microplastic pollution in Vembanad Lake, Kerala, India: The first report of microplastics in lake and estuarine sediments in India. Environmental Pollution, 222: 315–322.

Statistics Bureau of Xinjiang Autonomous Region (SBXAR). 2020. Xinjiang Statistical Yearbook 2020. Beijing: People's

Publishing House, 679–696. (in Chinese)

Taylor M L, Gwinnett C, Robinson L F, et al. 2016. Plastic microfibre ingestion by deep-sea organisms. Scientific Reports, 6: 33997, doi: 10.1038/srep33997.

Vaughan R, Turner S D, Rose N L. 2017. Microplastics in the sediments of a UK urban lake. Environmental Pollution, 229: 10–18.

Waldrop M P, Wickland K P, White I, et al. 2010. Molecular investigations into a globally important carbon pool: Permafrost-protected carbon in Alaskan soils. Global Change Biology, 16(9): 2543–2554.

Wang Z, Taylor S E, Sharma P, et al. 2018. Poor extraction efficiencies of polystyrene nano-and microplastics from biosolids and soil. PLoS ONE, 13(11): e0208009, doi: 10.1371/journal.pone.0208009.

Weithmann N, Möller J N, Löder M G, et al. 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Science Advances, 4(4): 80–87.

Windsor F M, Durance I, Horton A A, et al. 2019. A catchment–scale perspective of plastic pollution. Global Change Biology, 25(4): 1207–1221.

Wong J K H, Lee K K, Tang K H D, et al. 2020. Microplastics in the freshwater and terrestrial environments: Prevalence, fates, impacts and sustainable solutions. Science of the Total Environment, 719: 137–145.

Woodall L C, Sanchez-Vidal A, Canals M, et al. 2014. The deep sea is a major sink for microplastic debris. Royal Society Open Science, 1(4): 140317, doi: 10.1098/rsos.140317.

Xiong X, Wu C, Elser J J, et al. 2019. Occurrence and fate of microplastic debris in middle and lower reaches of the Yangtze River–from inland to the sea. Science of the Total Environment, 659: 66–73.

Yan M, Nie H, Xu K, et al. 2019. Microplastic abundance, distribution and composition in the Pearl River along Guangzhou City and Pearl River estuary, China. Chemosphere, 217: 879–886.

Yang D, Shi H, Li L, et al. 2015. Microplastic pollution in table salts from China. Environmental Science and Technology, 49(22): 13622–13627.

Yang G R, Chen L R, Lin D M. 2021. Status, sources, environmental fate and ecological consequences of microplastic pollution in soil. China Environmental Science, 41(1): 353–365. (in Chinese)

Yushanjiang A, Zhang F, Yu H, et al. 2018. Quantifying the spatial correlations between landscape pattern and ecosystem service value: a case study in Ebinur Lake Basin, Xinjiang, China. Ecological Engineering, 113(6): 94–104.

Zhang C, Chen X, Wang J, et al. 2017. Toxic effects of microplastic on marine microalgae *Skeletonema costatum*: interactions between microplastic and algae. Environmental Pollution, 220: 1282–1288.

Zhang C, Wang S, Sun D, et al. 2020. Microplastic pollution in surface water from east coastal areas of Guangdong, South China and preliminary study on microplastics biomonitoring using two marine fish. Chemosphere, 256: 127–132.

Zhang G S, Liu Y F. 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Science of the Total Environment, 642: 12–20.

Zhang H, Wang J, Zhou B, et al. 2018. Enhanced adsorption of oxytetracycline to weathered microplastic polystyrene: kinetics, isotherms and influencing factors. Environmental Pollution, 243: 1550–1557.

Zhang L, Xie Y, Liu J, et al. 2020. An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. Environmental Science and Technology, 54(7): 4248–4255.

Zhang S, Liu X, Hao X, et al. 2020. Distribution of low-density microplastics in the mollisol farmlands of Northeast China. Science of the Total Environment, 708: 135–145.

Zhang W, Wu C, Li Y, et al. 2021. Assessment of pile drivability using random forest regression and multivariate adaptive regression splines. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 15(1): 27–40.

Zhang Z Y, Li J Y., Mamat Z, et al. 2016. Sources identification and pollution evaluation of heavy metals in the surface sediments of Bortala River, Northwest China. Ecotoxicology Environment Safety, 126(1): 94–101.

Zhang Z Y, Yang X D, Yang S T. 2018. Heavy metal pollution assessment, source identification, and health risk evaluation in Aibi Lake of Northwest China. Environmental Monitoring and Assessment, 190(2): 69, doi: 10.1007/s10661-017-6437-x.

Zhang Z Y, Mamat Z, Chen Y G. 2020. Current research and perspective of microplastics (MPs) in soils (dusts), rivers (lakes), and marine environments in China. Ecotoxicology and Environmental Safety, 202: 110–117.

Zhang Z Y, Mamat Z, Wang P W. 2022. Occurrence and sources of microplastics in dust of the Ebinur lake Basin, Northwest China. Environmental Geochemistry and Health, 23(5): 128–138.

Zhou B, Wang J, Zhang H, et al. 2020. Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, east China: Multiple sources other than plastic mulching film. Journal of Hazardous Materials, 388: 121–128.

Zhou Q, Zhang H B, Zhou Y, et al. 2016. Separation of microplastics from a coastal soil and their surface microscopic features. Chinese Science Bulletin, 61: 1604–1611. (in Chinese)